Week 5: Part 3
Quorum-Based Consensus: Raft
Consensus Goal

Allow a group of processes to agree on a result

• All processes must agree on the same value

• The value must be one that was submitted by at least one process (the consensus algorithm cannot just make up a value)
We saw versions of this

- **Mutual exclusion**
  - Agree on who gets a resource or who becomes a coordinator

- **Election algorithms**
  - Agree on who is in charge

- **Other uses of consensus:**
  - Synchronize state to manage replicas: make sure every group member agrees on the message ordering of events
  - Manage group membership
  - Agree on distributed transaction commit

- **General consensus problem:**
  - *How do we get unanimous agreement on a given value?*
    
    \[
    \text{value} = \text{sequence number of a message, key=value, operation, whatever...}
    \]
Achieving consensus seems easy!

- One request at a time
- Server that never dies

value = "x=abc"
Dealing with failure

- **FLP Impossibility result**
  - *Impossibility of distributed consensus with one faulty process* by Fischer, Lynch and Patterson
  - Consensus protocols with asynchronous communication & faulty processes
    "every protocol for this problem has the possibility of nontermination, even with only one faulty process"

- It really means we cannot achieve consensus in bounded time
  - We can with partially synchronous networks
  - Either wait long enough for messaging traffic so the protocol can complete or terminate

References:
- original paper: https://dl.acm.org/doi/10.1145/3149.214121
Servers might die – let's add replicas

One request at a time
Reading from replicas is easy

We rely on a **quorum** (majority) to read successfully

No quorum = failed read!
What about concurrent updates?

We risk inconsistent updates
What about *concurrent updates*?

- Coordinator (or sequence # generator) processes requests one at a time
- But now we have a **single point of failure**!
- We need something safer
Consensus algorithm goal

Goal: agree on one result among a group of participants

Create a fault-tolerant consensus algorithm that does not block if a *majority of processes* are working

- Processors may fail (some may need stable storage)
- Messages may be lost, out of order, or duplicated
- If delivered, messages are not corrupted

**Quorum: majority (>50%) agreement is the key part:** If a majority of coins show heads, there is no way that a majority will show tails at the same time.

If members die and others come up, *there will be one member in common* with the old group that still holds the information.
Consensus requirements

• Validity
  – Only proposed values may be selected

• Uniform agreement
  – No two nodes may select different values

• Integrity
  – A node can select only a single value

• Termination (Progress)
  – Every node will eventually decide on a value
Distributed Consensus Protocols: Paxos

1 Introduction

Paxos 0.6 is a simple protocol that a group must use to decide on distributed actions. This simple protocol provides a way to achieve agreement among distributed processes. The basic idea is to start each proposal with a unique number. Higher numbered proposals override lower numbered ones. However, a proposal must not itself start the group of its proposal number. Before proposing a particular value, it first broadcasts from a majority of the group, the proposal incites no action unless a previous proposal is made. Otherwise, the proposal can only end up in a proposal.

The protocol has three steps. In the first round, the proposal incites a proposal number, n, and x, v is lower than the current proposal number in the group. The proposal incites from the group of proposals that the proposal number is higher than the last proposal number in the group. If x is not lower than the current proposal number, it finishes.

Paxos Made Simple

Leslie Lamport

11 Nov 2001

Paxos Made Practical

David Mazieres

This is a simple protocol that a group must use to decide on distributed actions.
Raft Distributed Consensus
Goal: replicated state machines

Allow a collection of systems to stay in sync and withstand the failure of some members

• Systems are deterministic – if they receive the same input then they produce the same results

• Required for any system that has a single coordinator

• Implement as a replicated log
  – Log = list of commands processed by each server in sequence
Consensus algorithm goal

Keep the replicated log consistent

- A consensus module on a server receives commands from clients
- It propagates the commands to consensus modules on other systems to get everyone to agree on the next log entry
- The entry is added to the log (queue) and a state machine on each server can then process the log data
Raft environment

- Server group = set of replicas (replicated state machine)
  - Typically a small odd number (5, 7)
- Clients send data to a leader
- The leader forwards the data to followers
- Each leader & follower stores a list of requests in a log
- Raft has two phases
  1. Leader election
  2. Log propagation
Participant states

• **Leader**: handles all client requests
  – There is only one leader at a time

• **Candidate**: used during leader election
  – One leader will be selected from one or more candidates

• **Follower**: doesn’t talk to clients
  – Responds to requests from leaders and candidates
Raft RPCs

• The Raft protocol uses two RPCs

• RequestVotes
  – Used during elections

• AppendEntries
  – Used by leaders to
    • Propagate log entries to replicas (followers)
    • Send commit messages (inform that a majority of followers received the entry)
    • Send heartbeat messages – a message with no log entry
• Each **term** begins with an election
• Any requests from smaller term numbers are rejected
• If a participant discovers its term is smaller than another’s
  – It updates its term number
  – If the participant was a **leader** or **candidate** then it reverts to a **follower** state

```
Term N  Term N+1  Term N+2
Log propagation  Election
```

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Leader Election

Everyone starts off as a *follower* and waits for messages from the *leader*

Leaders periodically send *AppendEntries* messages

- A *leader* must send a message to all followers at least every *heartbeat* interval
- These might contain no entries but act as a heartbeat

If a *follower* *times out* waiting for a heartbeat from a *leader*, it starts an election

- Follower changes its state to *candidate*
- Increments its term number
- Set a random election timeout
- Votes for itself
- Sends *RequestVote* RPC messages to all other members
  - Any receiving process will vote for this candidate if it has not voted yet in this term
Leader Election: Outcomes

Possible outcomes

1. **Candidate receives votes from a majority of servers**
   - It becomes a leader and starts to send `AppendEntries` messages to others

2. **Candidate receives an `AppendEntries` RPC**
   - That means someone else thinks they’re the leader – check the `term #` in the message
   - If `term #` in message > candidate's `term #`
     - It accepts the server as the leader and becomes a follower
   - If `term #` in message < candidate's `term #`
     - It rejects the RPC and remains a candidate

3. **Election timeout is reached with no majority response**
   - **Split vote**: if more than one server becomes a candidate at the same time, there is a chance the vote may be split with no majority
If more than one server becomes a candidate at the same time, there is a chance the vote may be split with no majority

• We want to avoid this situation

• Raft uses randomized timeouts to ensure concurrent elections and split votes are rare

• Election timeouts chosen randomly (e.g., in the range 150-300ms)

• Usually, only one server will time out –
  – winning the election and then sending heartbeats before others time out

• If multiple servers hold concurrent elections and we have a split vote
  – They simply restart their elections: it’s highly unlikely that both will choose the same random election timeout
Log replication: \textit{leader} to \textit{followers}

- Commands from clients are sent only to the current leader
  - Leader appends the request to its own log
    - Log entry has a term \# and an index \# associated with it
  - Sends an \textit{AppendEntries} RPC to all the followers
    - Retry until all followers acknowledge it

- Each \textit{AppendEntries} RPC request contains:
  - Command to be run by each server
  - Index to identify the position of the entry in the log (first is 1)
  - Term number - identifies when the entry was added to the leader’s log
  - Index and term \# of previous log entry
Log replication: followers

A follower receives an `AppendEntries` message

• If leader’s term < follower’s term
  – Reject the message

• If the log does not contain an entry at the previous (index, term)
  – Reject the message

• If the log contains a conflicting entry (same index, different term)
  – Delete that entry and all following entries from the log

• Add the data in the message to the log
Log replication: execution

• When a log entry is accepted by the majority of servers, it is considered committed

• The leader can then execute the log entry & send a result to the client

• Each **AppendEntries** RPC request also contains a commit index
  – Index of highest committed log entry

• When followers are told the entry is committed, they apply the log entry to their state machine
Forcing consistency

- Leaders & followers may crash
  - Causes logs (& knowledge of current term) to become inconsistent

- Leader tries to find the last index where its log matches that of the follower
  - Leader tracks `nextIndex` for each follower
    (index of next log entry that will be sent to that follower)
  - If `AppendEntries` returns a rejection
    - Leader decrements `nextIndex` for that follower
    - Sends an `AppendEntries` RPC with the previous entry
  - Eventually the leader will find an index entry that matches the follower’s

This technique means no special actions need to be taken to restore logs when a system restarts
The End